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ENERGY CHARACTERISTICS OF IONOSPHERIC DISTURBANCES AND NATURE OF THE STATES OF IONOSPHERIC AND GEOMAGNETIC DISTURBANCE

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SUMMARY

Comparison is made between the general planetary characteristic of the ionosphere disturbance ΔI_d and the energy characteristic E of the geomagnetic disturbance. It is shown that there is a correlation between the active periods of geomagnetic and ionospheric disturbances reflecting the structure of the magnetic field of the solar corpuscular stream and the force-free magnetic field. The relationship between ΔI_d and E is determined from the ionization balance equation for the entire ionosphere thickness. At the same time, the dependence on E of exosphere and ionosphere temperature variation is obtained from satellite deceleration. The question is discussed of the nature of energy transfer of the disturbance from the magnetosphere to the ionosphere by means of low frequency hydromagnetic waves dissipating in the ionosphere.

* * *

1. - Despite the significant advances in the ionosphere investigations attained during the IGY period and the subsequent years, the nature of ionospheric disturbance remains one of the least studied questions. There is currently no doubt that the corpuscular radiation of the Sun is responsible for the ionospheric disturbance. Meanwhile, it is clear that the direct penetration of the "cold" solar plasma into the undisturbed

* ENERGETICHESKAYA KHARAKTERISTIKA IONOSFERNYKH VOZMUSHCHENIY I PRIRODA GEOMAGNITNOY I IONOSFERNOY VOZMUSHCHENNOSTI.

magnetic dipole field is impossible even at high latitudes. The difficulty in the determination of the nature of ionosphere state of disturbance is linked with the relative localization of the disturbance course, the presence of effects of ionization decrease and increase in the F-region (often concomitantly observed at various latitudes and longitudes), and the still very scarce information on the character of the course of ionosphere disturbance in the entire region above the F_2-maximum, where the aggregate electron thickness is at least several times greater than the underlying one. It seems to us, that if we remain within the bounds of ionosphere measurements only, the ascertaining of the nature of the state of ionosphere disturbance will be impossible. It is necessary to assume a specific scheme of solar geoeffective flux action upon the Earth's magnetosphere and to consider the effect of the state of ionosphere disturbance as a part of the total transformation of the energy of solar corpuscular fluxes.

2. - The most general approach for the solution of the problem of the nature of the state of ionospheric disturbance is the determination of the energy of the ionospheric storm. First of all it is necessary to ascertain what is by order of magnitude the energy of the ionospheric disturbance and by what means it is transferred from the corpuscular stream to the ionosphere. There is ground to estimate that only a relatively small fraction of energy of geomagnetic variations is transformed in the ionosphere ($< 1 \div 10\%$).

The first step toward the energy analysis of the state of ionospheric disturbance may be the transition from the standard local (point) description of the storm to the two-dimensional (general planetary) consideration of the state of ionospheric disturbance, for example at the F_2-maximum level. It is evident that the absence of regular ionization measurements during the state of ionospheric disturbance in the entire thickness of the ionosphere, from the lower boundary to $\sim 3 \div 3.5\ R_E$, does not allow to resolve quantitatively the energy aspect of the state of ionosphere disturbance. There is, however, a good correlation between the aggregate ionization N of the aggregate thickness of the ionosphere and the electron concentration n_m at the F_2 - maximum level [1]. The quantity N was obtained in [2] in quiet and disturbed days by the Faraday effect at radiosignal reflection from the surface of the Moon. According to these observations the correlation of ΔN and Δn_m at the station Slau is considered in [3], and the time course of parameters Δf_0F2, ΔN $(\Delta f_0F2)^2$ and Δn_m for disturbed periods is compared also. Here Δf_0F2 denotes the deflection of the F_2-layer from the median during the disturbances of the critical frequency (in mc/s); ΔN and Δn_m are respectively the fluctuations of the total electron content in the entire ionized thickness and of the electron concentration at the F_2-layer maximum level from the undisturbed conditions. It was found that in the first approximation all these parameters agree well with one another and they may characterize not only the course of ionization at the F_2-maximum level but in the entire ionosphere thickness. We shall assume in the following that in the first approximation the two-dimensional (general planetary) description of ionization at the F_2-maximum level characterizes the total ionization in the entire atmosphere.

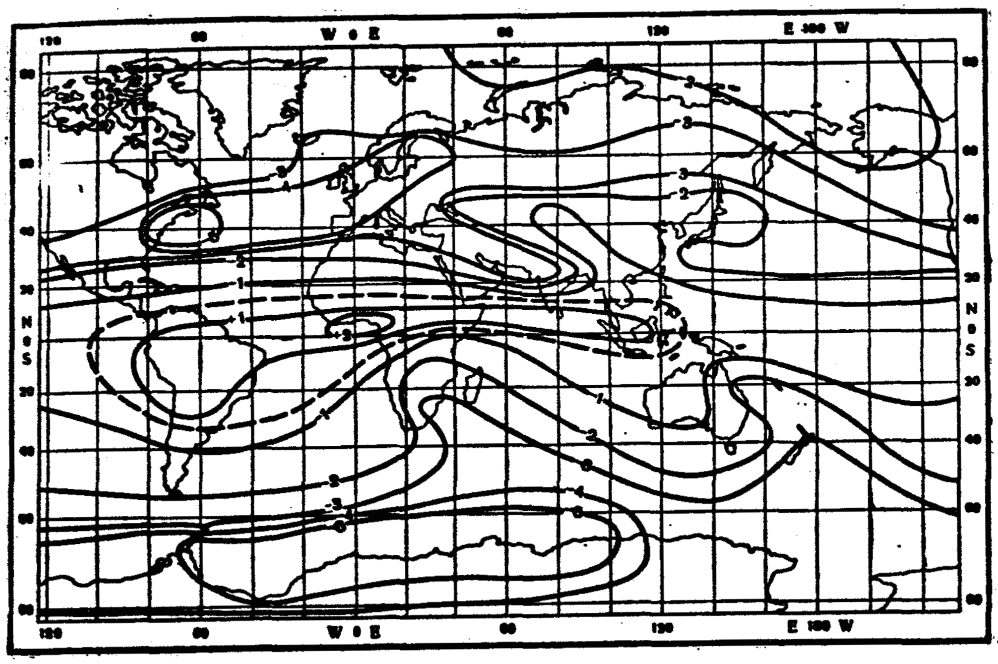


Fig. 1

3. - In order to obtain the general planetary characteristic of the state of ionosphere disturbance, we constructed for a series of ionospheric storms charts of Δf_0F2 deflections from the median of critical frequencies of the F_2-layer according to the world net of ionospheric stations. One such chart is presented in Fig. 1 for 1500 h. UT on 15 September 1957.

The consideration of hourly three-hour charts for ionospheric storms of the IGY - IGC allows to derive conclusions on the development of the state of ionospheric disturbance [4, 5]. One may also obtain from these charts the general planetary index of the state of ionospheric disturbance introduced in [3]. It is computed by the correlation

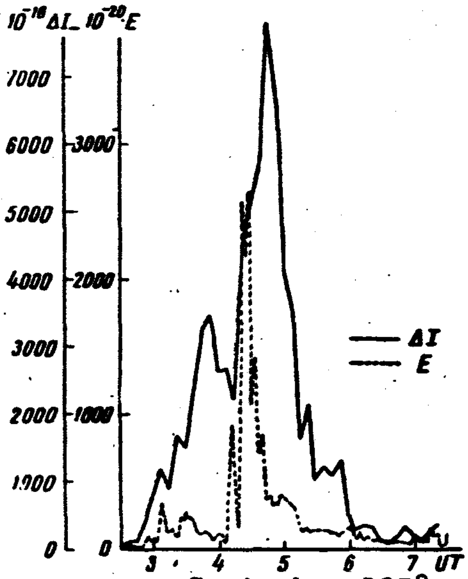
$$\Delta I_d = \sum_i^n (\Delta f_i F2)^2 \Delta S_i,$$

where ΔI_d is the state of disturbance index (hourly or three-hourly); ΔS_i is the area of the i-th portion of identical values of $\Delta f_{0i} F2$ on the indicated synoptical chart. The disturbance index is determined separately for the regions of overrated and underrated values of $\Delta f_{0i} F2$. Taking into account the above-referred to remark on the correlation of the index ΔI_d with the total ionisation N, we may assume that the index ΔI_d characterizes qualitatively the value of the general planetary energy of the state of ionosphere disturbance. It may be utilised for the analysis of the temporal course of ionosphere disturbance as well as for the comparison with the energy characteristic of the geomagnetic storm.

In order to ascertain the peculiarities of the relationship between the states of ionospheric and geomagnetic disturbance, we plotted three-hourly world synoptic charts of $\Delta f_0 F2$ for the following ionospheric storms: 1 — 9, 13 — 17, 21 — 24 September 1957; 3 — 7 September 1958; 25 — 30 March, 4 — 7 September 1959. During the considered disturbed periods the region of positive state of disturbance occupied an insignificant spot by comparison with the negative one; that is why the indices ΔI_+ were not compared with the geomagnetic data. Given in Fig. 2 is an example of comparison of the index ΔI_- with the energy index E of the geomagnetic disturbance for the greater disturbance of 3 — 7 September 1958 [6]. From the comparison of the curves it may be seen first of all that the active periods of gemoagnetic disturbance are also manifest (with a specific shift) in the ionosphere disturbance. The ionospheric storm is coming through not only in the general variation of ionization just as does the geomagnetic storm. There are, alongisde with the last maximum, general planetary maxima of variations (one or two "main periods" of disturbances) and several second-rate maxima. The shift Δt between the geomagnetic and ionospheric maxima (active periods) was found by epoch superimposition method (Fig. 3). The table below gives the correlation factors R between geomagnetic and ionospheric indices of active periods computed for various Δt, the duration of the considered storms being normalized to unity. The ratio $\mu = R/\sigma$, where σ is the root-mean-square error of R is given in the last column. As is well known, if $\mu \geqslant 3$, this may serve as one of the criteria of the fact that a real link exists between the correlating indices ΔI_d and E [7].

TABLE 1

Δt	$R \pm \sigma$	μ	Δt	$R \pm \sigma$	μ
0,0	0,59±0,04	15	0,12	0,54±0,04	14
0,02	0,72±0,03	24	0,12	0,32±0,06	5
0,04	0,69±0,03	23	0,20	0,29±0,06	5
0,06	0,73±0,03	24			
0,08	0,71±0,03	24	0,32	0,11±0,07	2
0,10	0,63±0,04	16			



September 1958

Fig. 2

Magnetic maximum

Fig. 3

It follows from the table and Figs. 2, 3 that:

a) there exists a real physical link between the separate active periods of the general planetary and the geomagnetic states of disturbance. At the same time, the **direct** reflection of separate active periods of a geomagnetic storm (members of "geomagnetic storm family" [8, 9]) by the corresponding periods of general planetary ionosphere state of disturbance is essential;

b) there exists a specific lag of ionosphere maxima relative to the magnetic maxima (0.05 time fractions of total storm, which corresponds to $\sim 2 - 6$ hours).

The geomagnetic variations at time of magnetic storm should be viewed as the superimposition of irregular D_i- variations and regular mean

D_{st}, S_p-, P-variations. Comparison of magnetic variations measured beyond the limits of the magnetosphere by Mariner-2 and on ground observatories [10] have shown that, apparently the greater part of D_i- variations reflect the distribution of the magnetic fields of separate plasma elements of corpuscular streams having their own magnetic field of free-force structure (M-elements). The energy of D_i-variations passes by the magnetosphere without substantial losses. At the same time the passage by the magnetosphere of a plasma element with an effective magnetic dipole moment M induces variations of the current systems of regular variations (D_{st}, S_p) on account of induction. The part of motion energy of M-element plasma, transferred by means of the magnetic field, remains in the magnetosphere and is partially transferred to the ionosphere. In this scheme [11], the total energy entering the ionosphere during the geomagnetic disturbance, constitutes a relatively small fraction ($\lesssim 1\%$) of the total energy of the geomagnetic disturbance, for the main part of energy, having entered the magnetosphere, is consumed for its heating and deformation. The shock waves, inducing this heating, dissipate to heights $\sim 3.5\, R_E$. Here, at boundary of abrupt density variation, [12] (Fig. 4, where [n_e] el cm^{-3}, [N] el cm^{-3}, [V_A] cm sec^{-1}, [P] erg cm^{-3}sec^{-1} is the power yielded at dissipation of hydromagnetic waves) an instability sets in and magnetosonic and Alfven waves are generated, which disintegrating in the ionosphere [13 – 15], induce its heating. The components of the "family" of geomagnetic storms reflect the relative closeness of the magnetosphere of the Earth to the chain of M-elements of the solar corpuscular stream (the main period of the storm is linked with the nearest passage of M-elements). The existence in the ionosphere disturbance of a correspondence to the components of the magnetic storm "family" points to the fact that the energy transfer from the magnetosphere to the ionosphere takes place by means of a relatively "low-inertia" mechanism, which reflects, as in the geomagnetic field, the spatial structure of M-elements of the solar corpuscular stream. This evidently does not exclude the presence of inertial components of ionosphere state of disturbance [D_{st}(F2), S_p(F2)], constituting, however, no more than 20-30% of the total energy.

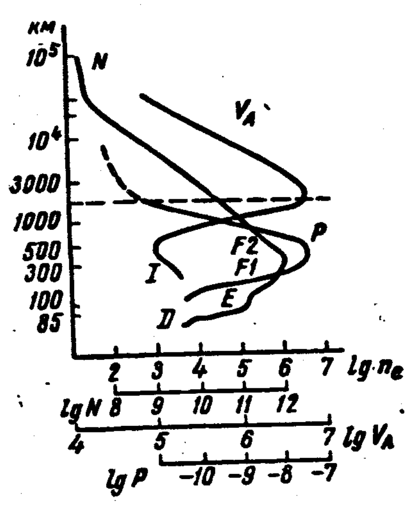


Fig. 4

4.- For the aims of the present work, we ought to clarify the relationship of total ionization variations in the ionosphere with the geomagnetic index (for example, a_p or E). To that effect we may assume in the first approximation that the ionization balance equation is described during ionosphere disturbances by the following expression :

$$dN_e / dt = Q(t) - \alpha N_e^2, \tag{1}$$

where N_e is the total electron content in the entire thickness of the F-region and higher, to the distance $\sim 3 \div 3.5\ R_E$; Q(t) is the number of ions and electrons forming at disturbance in the whole thickness; α is the mean effective recombination coefficient for the entire thickness.

The usual transfer term — $\operatorname{div}(N_e\bar{v})$, conditioned by diffusion, air masses shift etc., has not been taken into account in (1). But, when writing the equation for the entire thickness, this term, leading only to redistribution of the existing ionization (which contributes to the formation of respective maxima in height), may be disregarded. In the general case, taking into account the possible photochemical reactions for every level of the ionosphere [12], one must not only write the term αN^2, accounting for the recombination processes at collisions (of electrons, ions, various types of atoms and molecules), for which equality of both components' concentrations is assumed, but also the terms accounting for the diffusion. However, for the description of integral variations of the ionization we limit ourselves only to this recombination term. This can be done provided we take into account that the integral ionization is

$$N_e = \int_{h_{F1}}^{3R_E} n_e dz = \int_{h_{F1}}^{1500} n_e dz + \int_{1500}^{3R_E} n_e dz = N + N'. \tag{2}$$

We postulate, in correspondence with Fig. 4, that $N' \ll N \approx N_e$, that is, the basic ionization is concentrated in the region I to the height $\sim$1 500 km. Once these remarks have been taken into account, we may consider the solution of (1), given in the work [16], under the condition that Q (t) be a temporal function. It is well known that the equation (1) is in this case a Riccati-type equation, so that the expression

$$N = \left(\frac{Q}{\alpha}\right)^{1/2} - \frac{dQ}{dt}\frac{1}{4\alpha Q}. \tag{3}$$

can be considered as being its solution with a sufficient approximation.

During geomagnetic disturbances the basic energy liberation takes place in the considered region (I in Fig. 4, curve P); this energy liberation is linked with the dissipation of magnetohydrodynamic waves proceeding from the magnetosphere. The effect of geomagnetic disturbance is manifest in the heating of the ionosphere [17, 18] and in the variation of its temperature regime. At the same time

a) the effective recombination coefficient varies [12]

$$\alpha \approx \alpha_0 (T + \Delta T)^{-1}, \tag{4}$$

b) the total number of neutral atoms, which may be ionized in the entire thickness of the considered region (1) varies also. According to experimental data on satellite deceleration [19, 20]

$$N_0 = N_0' (T + \Delta T)^{3/2}, \tag{5}$$

c) the factor of photochemical reactions rate <u>k</u> varies too [12] on account of the change in the relative content of initial and final gas components defining Q (t). The dependence of the factor k on temperature according to [12, 17, 18], for example, is given by the correlation

$$k = k_0 (T + \Delta T)^{-0.3}. \tag{6}$$

In formulas (4) – (6) we took for ΔT [18 – 23]

$$\Delta T = A a_p \approx A' E, \tag{7}$$

where a_p is the amplitude characteristic of the geomagnetic disturbance, proportional to the energetic characteristic of E [9]; the factor $A \approx 10$. Substituting in (3) the expressions (4) – (7), we may obtain after not too complex transformations the following semiempirical expression for the variation of the total ionization:

$$\Delta N = N - N^0 = \Delta N_1 + \Delta N_2^2. \tag{8}$$

Here N^0 is the unperturbed value of the total electron content in the region I for the values of the geomagnetic index $E = 0$ and $dE/dt = 0$; ΔN_1 is the variation of the total electron content at $E \neq 0$ and $dE/dt \approx 0$ ΔN_2 is the same at $E \neq 0$ and $dE/dt \neq 0$. The subdivision of ΔN into ΔN_1 and ΔN_2 is justified by the fact that, according to [9, 13], there exist within the bounds of each term of "storm family" during geomagnetic disturbances periods with values $E \approx$ const and periods for which $dE/dt \neq 0$; they differ morphologically and apparently also by their character and tempo of energy ingress into the magnetosphere. The latter must also be reflected in the ionosphere's state of disturbance.

After some simplifications the expression for (8) will be

$$\Delta N = C_0 E^{1/2} + KE. \qquad (9)$$

The dependence of the variations of the total electron thickness on the energy E of the geomagnetic state of disturbance is plotted in Fig. 5. At great values of E and variations of E ($|dE/dt \gg 0$) the variations of the parameters C_0 and K ought to be taken into account. As is shown by the observations of [13], the index of E rises very steeply within the bounds of each elements of "storm family" ($dE/dt \gg 0$), while the drop takes place relatively smoothly. If we account for this when estimating the parameters C_0 and K in (9), we shall obtain the correlation of E and ΔN during one of the active disturbance periods, plotted in Fig. 6. The shift of maxima and a more stretched course of ΔN correspond to the observed correlation between the general planetary index of ionospheric disturbance ΔI and the geomagnetic state of disturbance E (see Fig. 2).

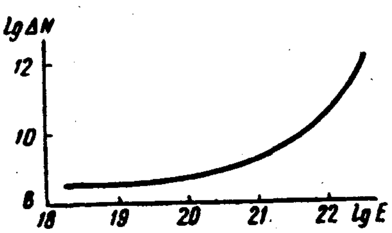


Fig. 5

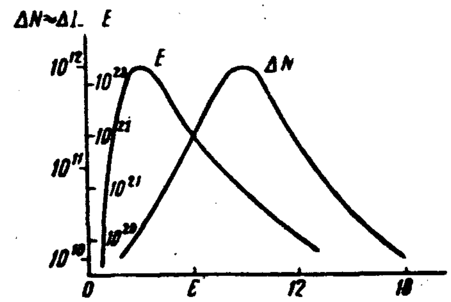


Fig. 6

5. - It was obtained in numerous investigations of magnetohydrodynamic waves in the magnetosphere and ionosphere (theoretically and partly corroborated by observations on AES Injun, Pioneer and Cosmos), that at dissipation of low frequency magnetohydrodynamic waves a notable heating of the ionosphere is possible. At the same time, observations on AES Cosmos-3, Cosmos-5 [24], Injun-III [25] and on geophysical rockets [26] have shown that there exists a flux of relatively energetic electrons (several tens kev) which may be responsible for the night and the disturbed ionization of the ionosphere. Calculations have shown that a simple emergence of energetic

electrons from radiation belts cannot ensure this observed flux of electrons, for in that case the radiation belts would be emptied in a short time without additional powerful boost. Without indulging further into this complex acceleration problem, having an interest in its own right, that is, heating of the magnetosphere plasma during geomagnetic disturbances, we shall note :

a) The interaction of the Earth's magnetosphere periphery with the solar corpuscular stream, consisting of separate plasma coaxials (M-elements) with force-free magnetic fields [10, 11, 23], naturally explains the deformation of the geomagnetic field and the appearance of a system of waves (shock, automodel, Alfvén and acoustic) dissipating in a different fashion at various heights of the magnetosphere [14, 27 — 29]. Thus, at great heights ($z \geqslant 3R_E$), where $v_A \gg v_s$ (v_A and v_s being respectively the Alfvén and sound velocities), the waves with frequencies $\leqslant 10 \div 10^2$ cps propagate without substantial damping, while the disintegration of Alfvén waves at these heights has no time to take place. In the regions, where $v_A \leqslant v_s$, the high-frequency ($\omega \gtrsim 10^2$ cps) waves dissipate during a time $> 3v_s/v_A\omega$. The disintegration of high-amplitude hydromagnetic waves($\gtrsim 10\gamma$), emerging as a consequence of instability during geomagnetic disturbances at heights of $2.5 \div 4.5\ R_E$, takes place in relatively dense regions (at heights $\lesssim 1\,500$ km with maximum near ~ 300 km (Fig. 6). The energy, then liberated, is sufficient for heating the ionosphere [15, 28], which, as was shown above, may satisfactorily explain the general decrease of the ionization during the active periods of geomagnetic disturbance.

2.- During geomagnetic storms the magnetic field in the magnetosphere represents, according to the adopted scheme in [10, 11, 30], the vectorial sum of the Earth's dipole field, the field of D_i-variations (magnetic field reflecting the distribution of the force-free magnetic field of flux's M-elements and the fields of regular variations (D_{st}, S_p). The latter, as pointed out above, constitute the consequence of induction effect in the magnetosphere at passage of the effective dipole field of flux's M-elements. Therefore, the variations of the magnetosphere's field will be essentially asymmetrical. Possible in this field are : a) the solar plasma injection [11], b) the substantial acceleration of protons, and particularly of electrons of magnetosphere plasma to energy of several tens of kev, provided the time of nonsymmetric field variations is greater than that of longitudinal drift of electrons or protons ($0.5 \div 1$ hour).

This condition is fulfilled, as a rule, during the time of geomagnetic disturbances, so that the mechanism of adiabatic and betatron acceleration of electrons in the magnetosphere, indicated by Parker [32], becomes possible. The fluxes of energetic electrons, observed in the ionosphere, may as well be explained by the flux of accelerated electrons at adiabatic acceleration, descending along the field, as by the injection of solar plasma into a nonsymmetrically distorted field. The former may be responsible for the ionization increase during disturbances. The ionization, really observed at various latitudes during ionosphere disturbances, is a result of simultaneous effect of both factors — additional ionization from the flux of energetic electrons and the intensive heating of the entire ionosphere at dissipation of hydromagnetic waves. During major disturbances and in the active periods of geomagnetic activity, the effect of ionosphere initial heating prevails at middle and higher latitudes.

**** THE END ****

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